The Physics Program at J-PARC

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Abstract. The Japan Proton Accelerator Research Complex (J-PARC) has been in construction under a cooperation of two institutions, KEK and Japan Atomic Energy Agency (JAEA, the former JAERI) since April, 2001. After a short summary of the current status of the project, the physics program in nuclear and particle physics at J-PARC is described.

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INTRODUCTION

The accelerators at J-PARC were proposed to provide MW-class proton beams at three different energies with the following components:

- A 400-MeV proton linac (normal conducting) to inject beams to a 3-GeV proton synchrotron (PS).
- A superconducting linac to accelerate protons from 400 MeV to 600 MeV. The 600-MeV proton beam will be used for R&D toward nuclear transmutation.
- The 3-GeV PS, operated at 25 Hz with 1 MW beam power, to be used primarily for materials and life sciences with neutrons and muons.
- A 50-GeV PS with slow extraction for kaon beams etc. and fast extraction for neutrino beams to SuperKamiokande.

The usage of various secondary particle beams (neutrons, mesons, antiprotons, etc.) that are produced in proton-nucleus reactions, together with daughter particles of the secondary beams such as muons and neutrinos, is the prime purpose of the project [1]. With these secondary and successive decay particles, three major scientific goals will be attained: a) nuclear and particle physics, b) materials and life sciences, and c) R&D for nuclear transmutation.

The J-PARC project is split into two phases as for the construction budget. The Phase 1 budget, which amounts to 151 billion yen, has been approved. It covers most of the accelerator components and part of the experimental facilities as shown in Fig. 1. The proton linac energy will be limited at 180 MeV at the initial stage, although the energy would be recovered rather easily by adding the linac components from 180 MeV to 400 MeV in near future. The operation of the 50-GeV PS will be limited up to 40 GeV for fast extraction and 30 GeV for slow extraction because of the limitations of power station capacities in Phase 1. Because of the limited linac energy, the beam power from the 3-GeV PS will be reduced to be $\sim$0.6 MW. The beam intensity in the 50-GeV PS will not be affected if we could inject more beam pulses from the 3-GeV PS than the original design. There is an idea to double the harmonic number of the 50-GeV PS to keep the beam intensity.

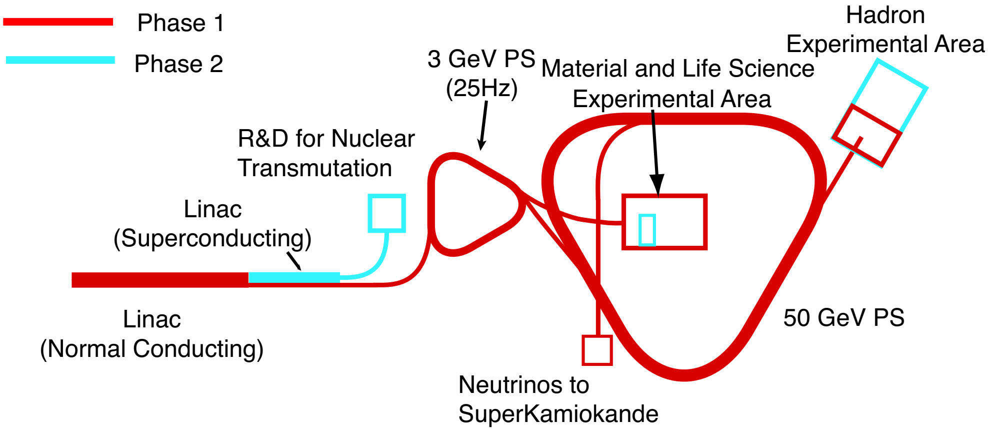

FIGURE 1. Layout of the JAERI/KEK Joint Project, J-PARC.

CONSTRUCTION STATUS

The construction of the LINAC and 3-GeV PS buildings is almost completed as shown in Fig. 2. The RFQ and two drift-tube linacs up to 40 MeV are already in place in the LINAC building. The separated drift-tube linacs downstream are also now under installation. The beam transport elements from the LINAC to the 3-GeV PS are already installed. We also started installation of the beam transport magnets from the 3-GeV PS to the material and life science experimental area. The 50-GeV accelerator tunnels are now under construction. About half of them are completed. Several dipole and quadrupole magnets have been installed in the tunnel, recently. The civil engineering for the neutrino beam tunnel and the hadron experimental area is recently started.

The current goal of the project is to complete the construction at the end of JFY2007. At that point, an expected beam power would be about 1% of the full beam power. It will take a year before reaching the level of 10% of the full power. We plan to open the facilities to general neutron users when the beam power reaches at 10% level. An anticipated usage for neutron users will start in the spring of 2009, whereas the usage for the 50-GeV beam lines will start by the end of 2008 even at the lower level of beam intensities. The neutrino beam will be ready in the spring of 2009, too.

PHYSICS PROGRAMS AT J-PARC

While the scientific fields to be investigated at J-PARC are very broad, here I will focus on nuclear and particle physics programs with kaon, neutrino, muon, and neutron beams.

In 2002, the Project Office called for Letters of Intent (LOI) for nuclear and particle physics experiments at 50-GeV PS. We received 30 LOI's in total at the Project Office.

FIGURE 2. A picture of the J-PARC construction site taken in September, 2005. The LINAC building (at the top left, white) and the 3-GeV PS building (triangular) are completed. The 50-GeV PS ring is under construction. A large building in the ring is the material and life science experimental facility. At the bottom right, we can find the construction site for the hadron experimental facility.

About 480 people are listed on the LOI's; $\sim$40% are Japanese, $\sim$30% North American, and $\sim$30% European. The Nuclear and Particle physics Facility Committee (NPFC) evaluated all the LOI's and recommended the neutrino proposal for the fast extracted beam line and two Day-1 experiments for the slow-extraction beam line. Also, they recommended a strategy of how to implement the other proposed experiments in the experimental area.

Nuclear Physics Programs

The nuclear physics experiments at J-PARC are to be carried out at the Hadron Experimental Facility in which the slow-extraction beam from the 50-GeV PS will be delivered. Unfortunately, in Phase 1, the area is limited to about a half of the designed size of the experimental hall. Thus, we will be only allowed to install one production target for secondary beam lines.

6 LOI's on strangeness nuclear physics which mainly require high-intensity kaon beams were proposed. The two Day-1 experiments were selected from these LOI's. 7 LOI's on hadron physics which require the primary proton beam or high-momentum hadron beams were also proposed for various interesting subjects. However, we will not be able to carry out these experiments in the initial stage of Phase 1 because of the limited space and the limited number of beam lines.

In the following sections, I will describe the two Day-1 experiments on strangeness nuclear physics, first.

The first experiment is entitled as "New Generation Spectroscopy of Hadron Many-Body Systems with Strangeness $S=-2$ and -1". By using the two separated kaon beam lines, K1.8 and K1.1, spectroscopic studies of hadronic many-body systems with $S=-2$ and $S=-1$ are proposed.

Spectroscopic Study of S=−2 Systems

The high-intensity K^- beam at $\sim$1.8 GeV/c is quite unique to open a new frontier of Strangeness Nuclear Physics in the spectroscopic studies of strangeness S=-2 systems. This is not only a step forward from the S=-1 systems as a natural extension, but also a significant step to explore the multi-strangeness hadronic systems; in the course of the limit, strange hadronic matter (S=-∞) in the core of a neutron star is our concern. Also, it is important to extract some information on ΞN and Λ-Λ interactions from the spectroscopic data.

The (K^-,K^+) reaction is one of the best tools to implant the S=-2 through an elementary process $K^-+p \to K^++\Xi^-$, the cross section of which in the forward direction has a broad maximum around 1.8 GeV/c.

The energy difference between the ($\Xi^- p$) system and the ($\Lambda\Lambda$) system is only 28.3 MeV in free space. Therefore, a relatively large configuration mixing between Ξ^-+A and $\Lambda\Lambda$+($A-1$) states is suggested. It is very interesting to investigate whether the single-particle picture of Ξ^- is valid or not in such a system.

For the spectroscopy of the (K^-,K^+) reaction, we need two spectrometers: a beam line spectrometer for the incident K^- and a K^+ spectrometer. The proposed K1.8 beam line was designed by H. Noumi *et al.*. A beam line spectrometer is installed in the last part of the beam line. For the K^+ spectrometer, we will use the existing SKS spectrometer with some modifications (Fig. 3). The overall energy resolution is estimated to be 2 MeV(FWHM) for a 2-g/cm^2 target thickness.

The production cross section of the Ξ-hypernuclei in the (K^-,K^+) reaction is calculated to be $\sim$0.1 μb/sr/MeV around the middle of the bound region for various types of potentials. Thus, the yield for the ^{208}Pb target with 2-g/cm^2 thickness is estimated to be $\simeq$ 6 events/MeV/day. For lighter targets such as ^{28}Si and ^{58}Ni, the yields are several times higher with the normalized target thickness of 2 g/cm^2.

High Resolution Hypernuclear γ-ray Spectroscopy

At the 50-GeV PS, we will be able to investigate almost all bound-state levels of various Λ-hypernuclei ranging from $^{4}_{\Lambda}$He to $^{208}_{\Lambda}$Pb. Measurements of angular correlations and polarizations of γ-rays allow us to assign spin-parities of states. We can thus clarify detailed level schemes of various hypernuclei and make “Table of Hyper-Isotopes” book, a hypernuclear version of the “Table of isotopes”. Such data will be used to extract properties and strengths of the YN and YY interactions and to discuss nuclear structure

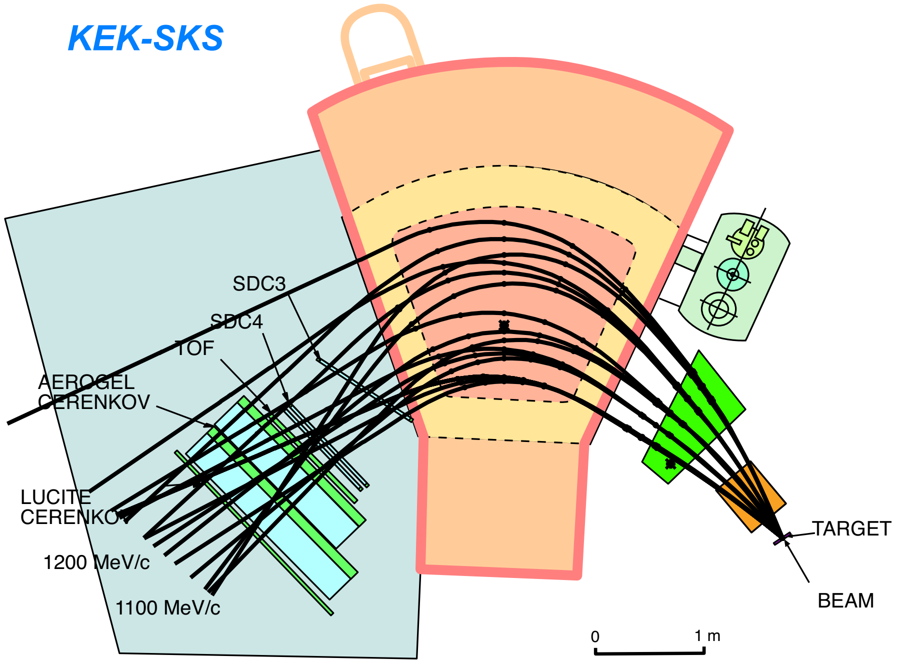

FIGURE 3. Schematic layout of the SKS spectrometer for the (K^-,K^+) reaction at 1.65 GeV/c.

change induced by a Λ as an impurity. Transition probabilities of $B(E2)$ and $B(M1)$ will be also measured for many hypernuclear transitions. $B(E2)$'s provide information on the size and deformation of hypernuclei, which are expected to be changed from those of normal nuclei because of a Λ particle. $B(M1)$'s allow us to extract a g-factor value of a Λ in a nucleus which may be modified from the free-space value.

The (K^-,π^-) reaction at 1.1 GeV/c is used in order to produce Λ hypernuclei. The momentum of the K^- beam is measured event-by-event with a beamline spectrometer having $< 0.2\%$ FWHM resolution. In the beginning stage, we will use the existing SPES II spectrometer, although the acceptance is not so large ($\sim$ 20 msr). The overall mass resolution better than 3 MeV is necessary.

Around the target, we install a new Ge detector system. In the present design, we expect to use 14 sets of "Segmented Super-Clover Ge detectors". One detector set consists of four Ge crystals of 7cm$\phi \times 14$ cm, and the electrode of each crystal is segmented into 4 readout channels. Such a fine segmentation is necessary for Doppler shift correction. The Ge crystals cover about 40% of the total solid angle. The Ge detector system has a photo-peak efficiency of 12% at 1 MeV in total.

We will have enough yields for almost all the γ transitions in the case of $^{12}_{\Lambda}$C for the 5-day data taking. We can expect good statistics even for γ-γ coincidence spectra, which enable us to completely reconstruct the level scheme.

Study of dense $\overline{K}$ nuclear systems

The second Day-1 experiment is an interesting experimental program to investigate the possible existence of dense $\overline{K}$ nuclear systems.

Very recently, possible presence of discrete nuclear bound states of $\overline{K}$ in light nuclear systems was predicted [3]. The $\overline{K}$-nucleus interaction was derived from $\overline{K}N$ interactions, which were constructed so as to account for i) the $\overline{K}N$ scattering lengths, ii) the K^--p atomic shift and iii) the energy and width of $\Lambda(1405)$. In these systems the strong attraction of the $I = 0$ $\overline{K}N$ interaction ($\overline{K}N^{I=0}$) plays an important role.

The strong attractive interaction of $I = 0$ $\overline{K}N$ helps accommodate a deeply-bound state, while contracting the surrounding nucleus, thus producing an unusually dense nuclear system. The exotic structure involving a $\overline{K}$ has also been studied by the Anti-symmetrized Molecular Dynamics method by Dote *et al.* [4]. This method can predict the density distributions of the constituent $\overline{K}$, protons and neutrons for the $ppnK^-$ system. The central nuclear density was found to be several times as much as the normal nuclear density.

Here I would like to emphasize that a new domain of physics paradigm will be opened in the study of $\overline{K}$ bound systems. Due to the very strong K^--p attraction, very deep discrete states of $\overline{K}$ are expected. They are predicted to have binding energies, $B_K \sim 100$ MeV. Since the predicted high-density systems are likely to be in a quark phase, the $\overline{K}$ bound states must provide a unique play ground for nuclear quark systems in well defined bound systems. It is natural to extend our consideration to multi-$\overline{K}$ systems, where more dense systems are expected to be formed. It has already been predicted that the most fundamental $S = -2$ systems, namely, ppK^-K^- and $ppnK^-K^-$, are strongly bound high-density systems. This leads to an exciting possibility that dense strange nuclei can be formed without the aid of gravity. Thus, these systems appear to be extremely important as “precursors" to kaon condensation and strange matter formation.

Various experimental searches are in progress by using various reactions: ^{4}He(K$^-_{stopped}$, n or p), in-flight (K^-, N), (K^-, π^-), and so on. Some positive results are already reported [5, 6, 7]. Also, the FINUDA group recently claimed the existence of a K^-pp bound state with an invariant-mass measurement of $\Lambda - p$ pairs [8].

The existence of the $\overline{K}$ bound states might be established before J-PARC. If not, it is very important to confirm these evidences at J-PARC. Anyway, it will be a very important experimental subject to be pursued at J-PARC.

Hadron Physics

Several interesting subjects were proposed in hadron physics. One of these subjects is proposed by S. Yokkaichi *et al.* on "Electron pair spectrometer at the JHF 50-GeV PS to explore the chiral symmetry in QCD". It is an extension of the KEK-PS E325 experiment with one order of magnitudes better statistics. A systematics study on mass modifications of vector mesons, such as ρ, ω, ϕ, in nuclear medium will be conducted by using the primary proton beam with a large-acceptance electron-pair spectrometer. The group reported an interesting recent result on the medium modification of ϕ meson in this conference [9].

Another important subject is the study of $\bar{d}/\bar{u}$ asymmetry of proton to be investigated in the Drell-Yan process with the primary proton beam proposed by J.C. Peng *et al.* Such an asymmetry was observed in NA51 experiment at CERN and measured in the low-x region in FNAL E866. The 50-GeV primary beam has a merit to extend the measurement at high-x region to test several theoretical models.

Particle Physics Programs

Main subjects in particle physics at J-PARC are a) neutrino oscillation experiments, b) CP- and/or T- violation measurements in kaon decays, and c) lepton-number violation, anomalous magnetic moment, and electric dipole moment measurements in muon, etc. Most of them are concerned with the physics beyond the standard model.

Neutrino Oscillation Experiment

A long-baseline neutrino oscillation experiment [10] is proposed by delivering a high-intensity neutrino beam from Tokai(J-PARC) to Kamioka(Super-Kamiokande); the distance is about 295 km and the beam intensity is $\sim$100 times higher than the previous neutrino beam intensity delivered from KEK 12-GeV PS. The neutrino beam line will be equipped with superconducting combined-function magnets. The neutrino production angle is declined by a few degrees from the primary proton beam axis, so that the neutrino beam energy has a narrow energy distribution. It has a great advantage to determine the neutrino oscillation parameters in high precision. The errors in mass difference Δm^2 and mixing angle $\sin^2 2\theta$ are expected to be 1×10^{-4} eV^2 and $\sim$0.01, respectively, in the five-year data taking. Another interesting subject in the neutrino oscillation experiment at J-PARC is to possibly detect the appearance of ν_e's through the oscillation of $\nu_\mu \to \nu_e$; nobody has ever observed it. The estimated sensitivity in $\sin^2 2\theta_{13}$ is $\sim$0.006 (at 90% C.L.) at $\Delta\mathrm{m}^2 \sim 3\times10^{-3}$ eV^2. This is an improvement by a factor 20 from the present lower limit.

Kaon and Muon Rare Decays

For the study of CP violation, the CKM matrix measurements with the $K_L \to \pi^0\nu\bar{\nu}$ and $K^+ \to \pi^+\nu\bar{\nu}$ decay modes were proposed. While the recent CKM matrix measurements in B decays have been successful, these measurements will give a complimentary check of the unitarity of the CKM matrix. Among them, the $K_L \to \pi^0\nu\bar{\nu}$ mode has a very small theoretical ambiguity. Thus, it is believed to be a clean and pure measurement. A high precision measurement of the branching ratio of better than 5% is proposed. Another interesting measurement is the T-violation muon polarization in the decays $K^+ \to \pi^0\mu^+\nu$ and $K^+ \to \mu^+\nu\gamma$. It is proposed to reach a statistical sensitivity of $\sim 10^{-4}$ in both decays.

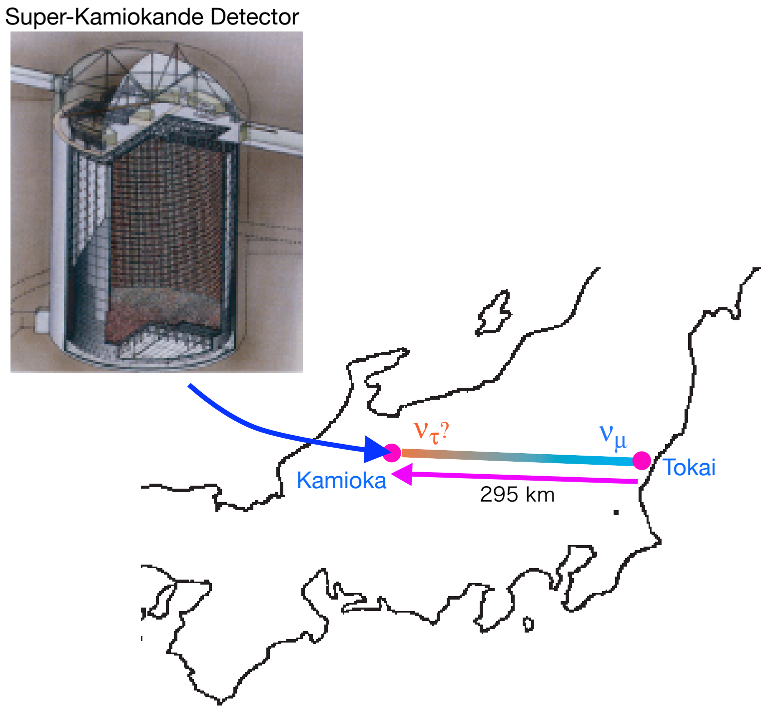

FIGURE 4. A long-baseline neutrino oscillation experiment T2K at J-PARC.

Although the construction budget is not included in the Phase 1 budget, a muon beam facility of the highest beam brightness in the world based on the phase-rotation technique was proposed. The facility is called "Phase Rotated Intense Slow Muon source" (PRISM). It would provide a muon beam having an intensity of about $10^{11} \sim 10^{12} \mu^{\pm}$/sec, a narrow momentum width of a few %, and no pion contamination. The PRISM beam momentum is relatively low (20 MeV in kinetic energy) for stopped muon experiments. Another muon source at aroud 500 MeV/c is proposed as PRISM-II. An R&D for the PRISM with an FFAG system is now on-goint at Osaka University [11].

By using these muon beams, the next generation muon experiments of the $(g-2)$ measurement with an improved uncertainty of 0.05 ppm, an electric-dipole-moment measurement at the $10^{-24} e \cdot cm$ level, and a search for lepton-flavour violating $\mu^- - e^-$ conversion at a sensitivity of 10^{-18} were proposed separately. These precision and sensitivity are expected to probe new physics beyond the standard model.

Fundamental Physics with Neutron

A T-violation experiment in neutron-nucleus scattering is proposed with a slow-neutron beam of $\sim$eV available at the material and life science experimental facility at 3-GeV PS. With a neutron flux of $4 \times 10^6 / s / cm^2 / eV$ at 0.5$\sim$1 eV available at J-PARC, a measurement of a ratio of T-violating to P-violating scattering amplitude in the polarized-neutron to polarized-nucleus (^{139}La) scattering with a sensitivity of 10^{-4}

is planned for a data taking period of 1.4×10^7 sec.

A new type of ultra-cold neutron (UCN) source is proposed as a future J-PARC facility. An extremely high-density UCN production of 3×10^5 UCN/cm^3 would be possible in superfluid helium by using a 500-MeV proton beam at 60 μA, based on a prototype test result at RCNP, Osaka. It will be very useful for next-generation neutron electric-dipole-moment measurements, high-precision β-decay measurements, etc.

SUMMARY

The construction of the high-intensity proton accelerator complex, J-PARC, is in progress in Japan. Three experimental facilities are to be constructed in the Phase 1 of the project: the hadron experimental hall, the neutrino beam line, and the material and life science facility. Kaon beams (in 2008), neutrino, and slow neutron beams (in 2009) will be available with the world highest intensity by improving the intensity step by step. Installations of new-generation muon sources and an ultra-cold neutron source are also proposed for future upgrades. Various interesting experimental programs in nuclear and particle physics are waiting for the beams.

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